The big picture of AGN feedback: Black hole accretion and galaxy evolution in multiwavelength surveys

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Abstract.
Large extragalactic surveys allow us to trace, in a statistical sense, how supermassive black holes, their host galaxies, and their dark matter halos evolve together over cosmic time, and so explore the consequences of AGN feedback on galaxy evolution. Recent studies have found significant links between the accretion states of black holes and galaxy stellar populations, local environments, and obscuration by gas and dust. This article describes some recent results and shows how such studies may provide new constraints on models of the co-evolution of galaxies and their central SMBHs. Finally, I discuss observational prospects for the proposed *Wide-Field X-ray Telescope* mission.

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INTRODUCTION

Recently, a number of galaxy evolution models have posited that feedback from active galactic nuclei (AGN) can play a key role in producing the observed evolution of galaxies and clusters (see [1] for a review). Feedback is observed most directly in clusters and groups, where AGN outflows interact strongly with hot X-ray emitting gas [2]. However, for galaxies in rarer environments or higher redshifts, the effects of AGN feedback are most apparent in the evolution of galaxies' stars and cold gas.

Large surveys comprising many thousands of galaxies and active galactic nuclei (AGN) have enabled precision measurements of luminosity functions, clustering, and evolution with redshift of both galaxies [e.g., 3, 4] and accreting supermassive black holes (SMBHs; [e.g., 5, 6]). Constrained by these observables, recent models have invoked different modes of feedback: radiatively-dominated ("quasar") modes, in which luminous quasars blow gas out of galaxies and terminate episodes of star formation, and kinetically-dominated ("radio") modes, in which lower-efficiency accretion produces outflows that prevent further cooling to form stars.

Models with these prescriptions have successfully reproduced, in broad terms, the luminosities, colors, and clustering of galaxies (derived mainly from optical and IR surveys) [e.g., 7, 8] as well as those of AGN (derived primarily from X-ray, optical, and radio data) [e.g., 9, 10]. However, in constraining models the galaxy and AGN observables are often treated *separately*, while the very nature of feedback implies that AGN and galaxies evolve *together*. Successful feedback models must therefore predict not only the observed distribution of AGN and galaxy properties, but AGN in different accretion states must be found in the appropriate host galaxies and environments.

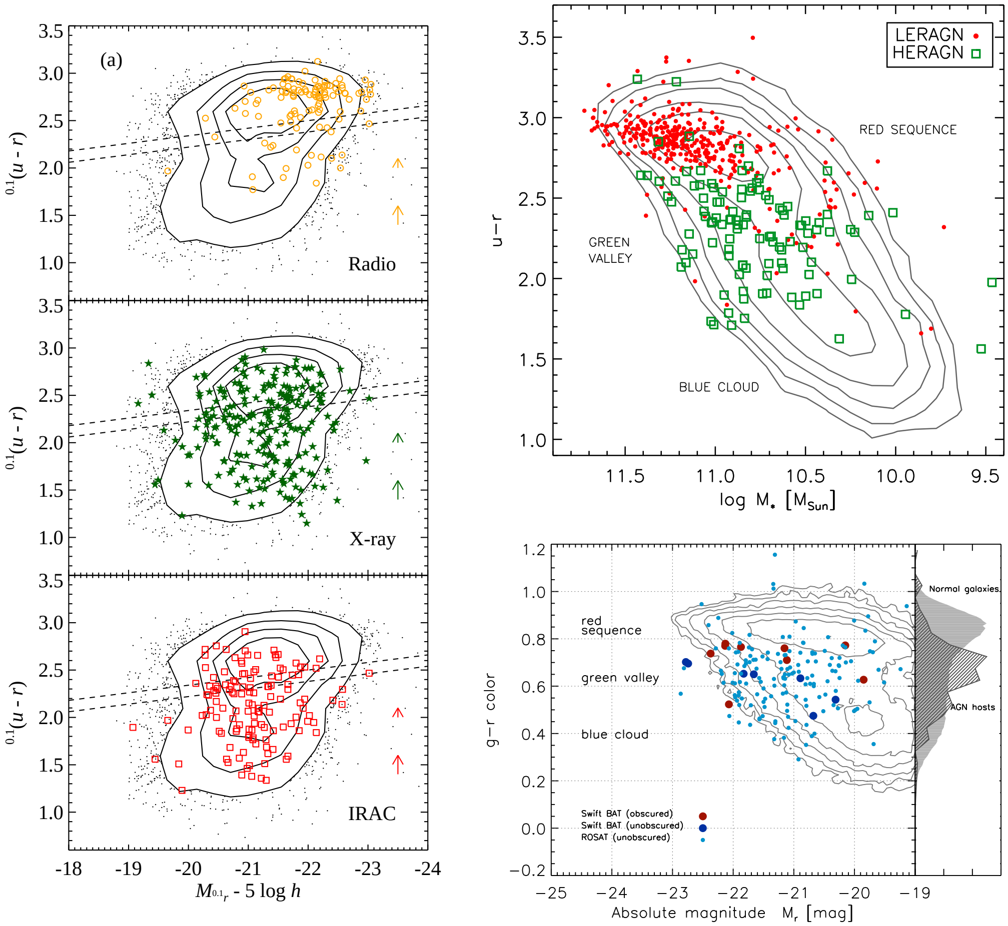

FIGURE 1. Colors and luminosities for AGN host galaxies, for AGN detected in the radio, X-ray and IR bands [11] (*left*), for radio AGN with high- and low-excitation emission line spectra [12] (*top right*), and for X-ray AGN [13] (*bottom right*). AGN in radiatively efficient states are typically found in blue cloud and "green valley" galaxies, while low-Eddington AGN populate the red sequence. Figures reproduced with permission of AAS.

AGN AND GALAXY EVOLUTION IN MULTIWAVELENGTH SURVEYS

Large multiwavelength surveys allow us to test these feedback scenarios directly, by observing galaxies and AGN within the same statistical samples. For example, Hickox et al. [11] used data from the 9 deg^2 Boötes multiwavelength survey to study the AGN and galaxy population at $z \sim 0.5$. Selecting AGN in the radio, X-rays, and infrared (IR), Hickox et al. found that AGN in different accretion states are found in markedly different host galaxies and large-scale environments (Fig. 1, *left*). Radio AGN, which primarily have low Eddington ratios ($\lambda < 10^{-3}$), are found in strongly clustered, luminous red galaxies, while IR AGN have high $\lambda > 10^{-2}$ and are found in weakly clustered, less luminous and bluer galaxies. X-ray AGN have intermediate to high λ and reside preferentially in "green" galaxies with clustering typical of the full galaxy population.

Smolčić [12] obtained similar results for a radio-selected sample in SDSS, with high-excitation (high-λ) radio AGN residing in "green" galaxies while the low-excitation (low-λ) objects lie on the red sequence (Fig. 1, *top right*). Correspondingly, Kauffmann and Heckman [14] found that in SDSS spectroscopic samples, the Eddington ratio distribution peaks at $\lambda \sim$ a few percent for galaxies with young stellar populations, but for older galaxies the distribution rises to very low Eddington ratios. These and a number of other recent results [e.g., 15, 16] suggest that black hole accretion broadly tracks the history of star formation in galaxies, with smaller, younger systems in rarer environments dominating both SMBH growth and star formation at later cosmic times.

To first order, these results are consistent with a picture in which energy from AGN helps heat or blow out reservoirs of gas, causing declines in both star formation and accretion. However, observations show that stellar populations and AGN activity do not evolve in lock step. IR AGN and optically-selected Seyferts appear to be more weakly clustered than normal galaxies matched in luminosity and color or stellar age [11, 17], while some studies have found that radio AGN are found in more massive dark matter halos than a control galaxy sample [18, 19]. This indicates that AGN fueling depends on local environment as well as the supply of cold gas. Further, it is not completely clear that AGN feedback *causes* star formation to decline. The X-ray AGN content in post-starburst galaxies is higher than for a control sample [20], and early-type galaxies hosting X-ray AGN have mainly "green" colors similar to post-starbursts (Fig. 1, *bottom right*[13]). However, for the Schawinski et al. [13] sample, the accretion timescale is shorter than that for stellar evolution, indicating that the observed AGN activity actually trails the shutoff of star formation. Clearly, even at relatively late times ($z < 0.7$) the interplay between black hole growth and star formation is complex and warrants a great deal of further study.

Observations at higher redshifts ($z \sim$ 2–3) probe the epoch of massive elliptical formation and peak quasar activity and allow us to test the most powerful modes of AGN feedback invoked to quench star formation in massive galaxies. Recent studies indicate that many $z \sim 2$ star-forming galaxies contain AGN [21, 22], but statistics are limited by the relatively small areas of the deepest X-ray fields. There also is some evidence that highly obscured AGN with rapid starbursts transition to a less obscured phase with declining star formation [e.g., 23], as might be expected for radiatively-dominated feedback [9]. Whether the quenching of star formation is caused by feedback or exhaustion of the fuel supply, and whether these episodes are primarily triggered by cold gas-rich mergers or other processes, remain open observational questions.

NEW OBSERVATIONAL TESTS

These and many other recent results provide motivation for more detailed observations of the co-evolution of AGN and stellar populations over a range of redshifts. A practical observational goal is to derive AGN observables (such as luminosity functions and clustering) *as a function of host galaxy properties*, and then compare these directly to the output of hydrodynamic or semi-analytic evolution models. Such studies are particularly well-suited to X-ray observations which, although they can miss weak or highly obscured AGN, are the most efficient and complete tracers of accretion at

relatively high redshifts ($z > 1$). Some recent works have begun to study X-ray AGN clustering and luminosities in bins of host galaxy properties [e.g., 16, 24, 25], but these are still limited by relatively small numbers of objects. Large-area sensitive surveys with *Chandra* and *XMM* would enable significant advances, but a very large step forward will come from the next generation of wide-field X-ray surveys. In particular, the proposed *Wide-Field X-ray Telescope*[1] would perform large surveys to detect $> 10^7$ AGN, of which $> 10^6$ would have host galaxy colors and morphologies derived from optical and IR imaging. The *WFXT* sample would enable high-precision luminosity functions and clustering measurements (comparable to those currently available for all X-ray AGNs) in each of > 20 bins of galaxy luminosity, mass, or stellar age, as well as in 4–5 bins of redshift. Thus *WFXT* would directly trace the co-evolution of black holes and galaxies in unprecedented detail, providing exciting insights into the nature of feedback.

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[1] `http://wfxt.pha.jhu.edu/`